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Biochar Application in Soils Mitigate Climate Change through Carbon Sequestration

Rajiv Rakshit[1*], Ashok K. Patra[1], Anupam Das[2], Debarup Das[1]

[1]Division of Soil Science and Agricultural Chemistry, IARI, New Delhi (110 012), India
[2]Division of Agricultural Physics, IARI, New Delhi (110 012), India

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Correspondence to

[*]*E-mail*: rajiv.ssaciari@gmail.com

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Abstract

There is a large imbalance between carbon release to the atmosphere and carbon uptake by other compartments which leads to a continued increase in atmospheric CO_2. Production of biochar formed by pyrolysis of biomass and its storage in soils has been suggested as a means of abating climate change by sequestering carbon. Biochar technology can be a novel approach to retain carbon in a stable form that can be stored outside of the atmosphere for longer time periods. The principal mechanisms operating in soils through which biochar entering the soil is stabilized and significantly increase its life cycle in soil are its particulate nature, recalcitrance, mean residence time and interaction with mineral surfaces.

1. Introduction

Carbon is the most abundant element in living things and accounts for approximately 50% of the total mass of plants and animals. It is well known that the global carbon cycle is closely connected to global climate change largely through anthropogenic emissions of carbon dioxide originating from fossil fuel use and land use change (IPCC, 2007). Atmospheric concentration of CO_2 has increased from ~ 280 ppm in pre-industrial era to ~ 385 ppm in 2008 (+37.5%) and is presently increasing at the rate of ~ 2 ppm yr^{-1} or 3.5 Pg yr^{-1} (1Pg = 1 billion metric ton) (IPCC, 2007). There exist a strong link between food insecurity and climate change. The twin crisis of climate change and food insecurity can be addressed by restoring soil organic carbon pool through carbon sequestration in agro-ecosystems, especially in agricultural soils. The global potential of C sequestration in soils of agro-ecosystems is about 2.1 billion tons C $year^{-1}$ (Lal, 2010). Increase in soil C pool leads to reduction in atmospheric concentration of CO_2 because a part of the photosynthesized biomass is converted into stable humus with a long mean residence time in soil. There are a number of options for carbon sequestration in agro-ecosystems (Lal, 2011) but the modern approach is the soil application of biochar, charcoal created by low-temperature pyrolysis of biomass under anaerobic conditions (Zimmeman, 2010). Biochar is receiving much attention as a potential tool for mitigating climate change through long-term biological carbon sequestration. Biochar is rich in carbon and, depending on its ultimate use; the biochar may retain the carbon, thereby delaying or completely preventing the release of the carbon in the form of carbon dioxide. The potential of biochar application for soil organic carbon sequestration may be 1 billion tons C $year^{-1}$ (Sohi et al., 2010) or more (Lehmann et al., 2006).

2. Biochar

Biochar is defined as: “charcoal (biomass that has been pyrolysed in a zero or low oxygen environment) for which, owing to its inherent properties, scientific consensus exists that application to soil at a specific site is expected to sustainably sequester carbon and concurrently improve soil functions (under current and future management), while avoiding short- and long-term detrimental effects to the wider environment as well as human and animal health” (Verheijen et al., 2009). In more technical terms, biochar is produced by so-called thermal decomposition of organic material under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C). Higher chemical stability and carbon content and its potential to reside in soil over decades, makes it a potential sink of carbon. The transformation of labile plant organic matter into biochar through pyrolysis not only reduce CO_2 emissions from energy production, but biochar additions to the soil constitutes a net withdrawal of carbon dioxide from the atmosphere. Thus, biochar could play an important role in helping to sequester carbon from the atmosphere.

3. Carbon Sequestration

Soil carbon sequestration is the process of transferring carbon dioxide from the atmosphere into the soil through crop residue and other organic solids, and in a form that is not immediately reemitted to either mitigate or defer global warming and avoid dangerous climate change. Carbon dioxide is absorbed by trees, plants and crops through photosynthesis and stored as carbon in biomass in tree trunks, branches, foliage and roots and soils (Environmental Protection Agency). Forests and stable grasslands are referred to as carbon sinks because they can store large amounts of carbon in their vegetation and root systems for long periods of time. Soils are the largest terrestrial sink for carbon on the planet. World soils constitute the third largest global C pool, comprising of two distinct components: (i) soil organic C (SOC) estimated at 1550 Pg, and (ii) soil inorganic C (SIC) pool estimated at 950 Pg, both to 1-m depth (Lal, 2004).

4. Stability of Biochar: Causes

Stability of biochar is an important aspect since only a long half life will ensure a relevant sequestration potential. Stability determines how long carbon applied to soil as biochar will remain sequestered in soil and how long it may influence emissions of greenhouse gas from the pedosphere and contribute to the mitigation of climate change. Conversion of biomass to biochar followed by application of biochar to the soil increases the residence time of carbon (C) in the soil relative to the application of the same biomass directly to the soil, and therefore can be considered over particular timescales to result in a net withdrawal of atmospheric CO_2 (Lehmann, 2007). Biochar must be of significantly greater stability in the environment in order to extend the duration of its benefits. Therefore, biochar must be of significantly greater stability in the environment than other organic matter in order to extend the duration of its benefits. The principal mechanisms which stabilize biochar are intrinsic recalcitrance, spatial separation of decomposers and substrate, and formation of interactions between mineral surfaces (Sollins et al., 1996).The relatively stable nature of organic matter protected within aggregates or through the formation of organo-mineral interactions may also be of relevance to the stability and longevity of biochar in soil. Few important factors are discussed as follows:

4.1. Mean residence time

One of the distinguishing properties of biochar is its high stability in the environment relative to other types of organic C substances. It can persist up to 13,900 years in deep-sea environments (Masiello and Druffel, 1998) and was found to have a mean residence time of 10,000 years in soils (Swift, 2001). Lehmann and co-workers in 2008 reported a mean residence times of 1300 to 2600 years. However, long-term simulations show biochar-C can reside for >100 to 2000 years. Components of the carbon in biochar are highly recalcitrant in soils, with residence times for wood biochar being in the range of 100s to 1,000s of years, which is around 10-1,000 times longer than residence times of most soil organic matter (SOM) (Verheijen et al., 2009). Therefore, biochar addition to soil can provide a potential sink for C. Consequently, this would reduce the CO_2 release back to the atmosphere if the carbon is indeed persistently stored in the soil.

4.2. Recalcitrance

Biochar is made up of biologically recalcitrant carbon that is not easily mineralized by the soil microbial community (Chan and Xu, 2009). The C in biochar is held in aromatic form which is resistant to decomposition when added as a soil amendment (Amonette and Joseph, 2009), making it a carbon sequestration tool. The conversion of organic matter to biochar by pyrolysis significantly increases the recalcitrance of C in the biomass. The composition changes through a complete destruction of cellulose and lignin and the appearance of aromatic structures (Paris et al., 2005). These changes in the composition of organic bonds by pyrolysis have a significant effect on the stability of biochar.

4.3. Particulate nature

The particulate form may have an important role in decreasing decomposition rates of biochar. Oxidation of biochar particles starts at its surfaces (Cheng et al., 2006) and typically remains restricted to the near-surface regions even for several millennia (Cohen-Ofri et al., 2007). Therefore, its particulate nature may lend stability to biochar, where the outer regions of a biochar particle protect the inner regions from access by microorganisms and their enzymes.

4.4. Interactions with mineral surfaces

Biochar is found in the organo-mineral fraction of soil (Liang et al., 2008), revealing that biochar interacts with minerals. Association of biochar surfaces with Aluminium (Al) and Silicon (Si) and, to a lesser extent, with Iron (Fe) was found during the first decade after addition of biochar to soil which increased more slowly within biochar structures (Nguyen et al., 2008). Coating of biochar particles with mineral domains is frequently visible in soils (Lehmann, 2007) and suggests interactions between negatively charged biochar surfaces and either positive charge of variable-charge oxides by ligand exchange and anion exchange, or positive charges of phyllosilicates by cation bridging. Similarly, Calcium (Ca) was shown to increase biochar stability, most likely by enhancing interactions with mineral surfaces (Czimczik and Masiello, 2007). These complexation reactions between biochar surfaces and polyvalent metal ions increase biochar stability.

5. Carbon Sequestration Potential

The sequestration potential depends on climate, soil type, and site specific management. Soil organic carbon of cropland increases only if either soil organic carbon additions are enhanced or decomposition rates reduced (Sauerbeck, 2001). Reduced decomposition is an advantage of charcoal (biochar). As the soil organic carbon pool declines due to cultivation, the more resistant charcoal fraction increases as a portion of the total carbon pool and may constitute up to 35% of the total soil organic carbon pool in ecosystems (Skjemstad et al., 2002). Only 2-20% of the carbon added as above ground residues and root biomass enters the soil organic carbon pool by humification. The rest is converted to CO_2 due to oxidation (Lal, 2004). Soils can only sequester additional carbon until the maximum soil carbon capacity, or soil carbon saturation, is achieved, which requires a steady input of biomass and careful management practices. In contrast, about 50% of the carbon can be captured if biomass is converted to biochar (Lehmann et al., 2006). Globally, soil is estimated to hold more organic carbon (1,100 Gt; 1 Gt=1,000,000,000 tonnes) than the atmosphere (750 Gt) and the terrestrial biosphere (560 Gt) (Post et al., 1990; Sundquist, 1993). The principle of using biochar for carbon sequestration is related to the role of soils in the carbon cycle. The global flux of CO_2 from soils to the atmosphere is in the region of 60 Gt of carbon per year. This CO_2 is mainly the result of microbial respiration within the soil system as the microbes decompose soil organic matter (SOM). Biochar are considerably more recalcitrant than soil organic matter and decomposes very slowly, over a time frame. Thus, biochar allows more carbon input as compared to the carbon output and this is the basis behind biochar's possible carbon negativity and hence it's potential for climate change mitigation. Further, biochar is highly stable against microbial decomposition and applying this to farmland has the potential to mitigate GHG emissions. Not all agricultural waste materials are suitable to produce bio-char, including many field or vegetable crop residues with the notable exception of rice husks (FFTC, 2001), which has high concentrations of silica entrapping carbon during combustion (Raveendran et al., 1995). Rice husks are typically regarded as a waste product, but can be used to sequester carbon by producing bio-char. Further, studies showed that the highest biochar carbon sequestration is achieved at 500°C, despite the fact that biochar made at higher temperatures is relatively more recalcitrant than low temperature biochars. However, CO_2 is also emitted throughout the biochar life cycle including pyrolysis, transportation, and farmland application. Therefore, estimating the net carbon sequestration potential by considering these CO_2 emissions is important. Kameyama et al., (2010) carried out a study on Miyako Island (Japan) to estimate the net carbon sequestration potential of farmland application of bagasse charcoal produced by the pilot plant. The net carbon sequestration potentials, including all CO_2 emissions and carbon stabilised as charcoal, for the pilot plant using dry and wet feedstock were estimated to be 0.3 and 0.2 t CO_2 t^{-1} dry weight for dry feedstock (MC 20%) and wet feedstock (MC 50%), respectively. These values corresponded to 70% and 50% of the carbon stabilised as bagasse charcoal. CO_2 mitigation potential with farmland application of bagasse charcoal on Miyako Island were calculated to be 1200–1800 t CO_2 $year^{-1}$ and 60–90 t CO_2 ha^{-1}, based on net carbon sequestration of 0.2–0.3 t CO_2 t^{-1} DW, if the available bagasse (12,000 tonnes $year^{-1}$) is applied to farmlands on the Island as bagasse charcoal. Lehmann et al., (2006) predicted that the biochar storage capacity of global cropland and temperate grassland is ~400 Gt C, which would be equivalent to a ~25% increase in global soil carbon. Using this data, Lenton and Vaughan (2009) calculated a reduction in atmospheric carbon of up to 22 Gt C (equivalent to a reduction of 10 ppm CO_2) by 2050. Continuing the trend forward, they predicted 3.15 Gt C yr^{-1} could be sequestered by 2100, which they calculated resulted in a total biochar reservoir of 148 Gt C and a corresponding atmospheric removal of 79 Gt C (37 ppm CO_2). Assuming an addition of 3% of biochar (by mass) into the top 30 cm of the total agricultural land area (standing at around 45 million km^2 worldwide), the capacity worldwide would be 600 Gt C of biochar (Saxton et al., 1986). Lehmann et al., (2006) estimate a potential global C-sequestration of 0.16 Gt yr^{-1} using current forestry and agricultural wastes, such as forest residues, mill residues, field crop residues, and urban wastes for biochar production. Using projections of renewable fuels by 2100, the same author estimate sequestration to reach a potential range of 5.5-9.5 Gt yr^{-1}, thereby exceeding current fossil fuel emissions. However, the use of biochar for climate change mitigation focuses on the effects of biochar addition to soils with regard to physical, chemical and biological effects, as well as related effects on soil and ecosystem functioning. Studies regarding "The Carbon Sequestration by Forestation and Carbonisation" (CSFC) scheme (previously called CFC) estimated that 368,000 t $year^{-1}$ of biomass residue and waste which were disposed from the plantation and pulp mill could be transformed into 77,000 t year^{-1} of charcoal, if conventional charcoal producing methods are used. It was also expected that the carbon emission reduction by the project could reach up to 62,000 t C year^{-1} (or 230,000 t CO_2) (Okimori et al., 2003). Thus, presented studies showed that biochar posses a very high potential of sequestering carbon (Table 1).

Table 1. Carbon sequestering potential of various feedstocks

Feed stock	CSP (Gt C year^{-1})	References
Forest residues	0.021	FAO, 2004
	0.012	Walsh et al.,1999
Mill residues	0.024	Walsh et al.,1999
Rice husk	0.038	Raveendran et al.,1995
Groundnut shells	0.002	FAO, 2004
Urban waste	0.16	Walsh et al.,1999
Agricultural and Forest residues	0.16	Lehmann et al., 2006

CSP: Carbon sequestration potential

6. Conclusion

Biochar technology can be a novel approach for establishing a sink for soil carbon sequestration. The interaction mechanisms with different soil constituents, behaviour and fate in different soil types and management practices especially under long-term condition, its yield and stability should be studied to have a better understanding of biochar in soil systems. So, wide-scale dissemination of biochar technology for carbon sequestration and climate change mitigation need intensive investigation.

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